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Studies for the Loss of Atomic and Molecular Species from Io

William H. Smyth

Atmospheric and Environmental Research, Inc.
840 Memorial Drive
Cambridge, MA 02139-3794

Report for the Periods of
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I. Introduction

The general objective of this project is to advance our theoretical understanding of Io's atmosphere by studying how various atomic and molecular species are lost from this atmosphere and are distributed near the satellite and in the circumplanetary environment of Jupiter. The project is divided into well-defined studies described for the likely dominant atmospheric gases involving species of the SO_2 family (SO_2, SO, O_2, O, S) and for the trace atmospheric gas atomic sodium. The relative abundance of the members of the SO_2 family and Na (and its parent NaX) at the satellite exobase and their relative spatial densities beyond (i.e., in the extended corona of Io) are not well known but they will depend upon a number of factors including the upward transport rate of gases from below, the velocity distribution and corresponding escape rate of gases at the exobase, and the operative magnetospheric/solar-photon driven chemistry for the different gases. This question of relative abundance will be studied in this project.

In order to address this question, we will undertake theoretical modeling studies for the distribution and time variability of these exospheric gases in Io's corona/extended clouds and will evaluate the importance of various physical processes that shape their relative abundances and escape rates. Our primary objective will be to study near-Io emission observations for O, S, and Na, most of which have already been acquired and some of which are scheduled to be acquired in 1996-1997 as part of the larger coordinated International Jupiter Watch Observational Campaign to support the Galileo mission. A secondary objective will be to continue the study of various larger-spatial-scale ground-based sodium and spacecraft (Voyager and Galileo) SO_2^+ observations in order to address related issues and to lay the groundwork for larger-spatial-scale O and S observations likely to be obtained in the near future. The proposed studies are of scientific importance in understanding (1) the atmosphere of the satellite, (2) the interactions of the magnetospheric plasma and the atmosphere, (3) the nature and composition of the heavy ion sources for the plasma torus, (4) the impact of these gases on the larger magnetosphere, and (5) the spatial distribution of these gases in the magnetosphere and beyond in the larger solar wind environment.

Near-Io observations for this project will be made available in four collaborative efforts established with

(1) F. Scherb of the University of Wisconsin-Madison who from ground-based facilities in 1990-1996 very successfully obtained synoptic observations of [O I] 6300 Å emission near Io and in 1996-1998 will continue these synoptic observations, search for [O I] 5577

Å emission, and add a new Fabry-Perot program element using the new WIYN telescope at Kitt Peak to obtain very-high spatial resolution images near Io in the [O I] 6300 Å and Na 5890 Å emission lines,

(2) G. E. Ballester of the University of Michigan who with HST has acquired cycle IV and will be acquiring cycle V observations for O and S near Io in various UV emission lines,

(3) L. M. Trafton of the University of Texas who has obtained in 1984-1989, and in his ongoing program in 1995 and 1996, groundbased observations for the north-south spatial distribution and spectral line shape of sodium (5890 Å, 5896 Å) emissions near Io, and

(4) N. M. Schneider of the University of Colorado-Boulder who obtained in 1987 from groundbased facilities an extensive set of observations for the east-west spatial distribution and spectral line shape of sodium emissions near Io, which exactly overlap the October 1987 observations of Trafton.

These near-Io emissions exhibit time variability with Io System III longitude and Io east-west location. The general three year plan of research for these studies is outlined in Table 1.

II. Summary of Work Performed in the Third Bi-Monthly Period of Year Two

Work accomplished in the third bi-monthly period of the second project year includes (1) a continuation of the assessment of the electron-impact neutral emission rates for atomic oxygen and sulfur, and (2) the addition of atomic hydrogen in the neutral cloud model.

2.1 Electron Impact Emission Rates for Atomic Oxygen and Sulfur Lines

In the report for the first bi-monthly period of this project, the electron impact emission rates for various lines were calculated and reported using the Collisional Radiative Equilibrium (COREQ) model developed by D. E. Shemansky with updated atomic data files for atomic oxygen and sulfur also supplied by D. E. Shemansky. These emission lines are important in modeling and studying the ultraviolet and visible brightnesses of atomic oxygen and sulfur in Io's corona and extended neutral clouds. In our collaboration with Dr. G. E. Ballester of the University of Michigan, we have undertaken preliminary comparison of the calculated and observed relative strengths of various ultraviolet emission line multiplets of interest for atomic oxygen and sulfur measured near Io. In a number of important cases, this agreement is poor, suggesting that the incomplete atomic data upon which the calculations are based require improvement. The matter is presently under further study by Dr. G. E. Ballester to ascertain the nature of the disagreements and to determine possible improvements to be incorporated in the calculation of the emission rates. Clearly detailed laboratory measurements would be very useful, particularly for atomic sulfur.

2.2 A Neutral Cloud Model for Atomic Hydrogen

Atomic hydrogen has been added to the neutral cloud model for Io. This has been motivated by (1) the recent discovery of atomic hydrogen observed in the Lyman-α emission line in Io's atmosphere near both the northern and southern polar regions (Roesler et al 1998), which was reported in the last bi-monthly progress report, and (2) the detection of pickup H^+ ions in the near vicinity of Io by the PLS instrument of the Galileo spacecraft (Frank 1998). The inclusion of atomic hydrogen in the neutral cloud model requires the specification, implementation, and calculation of the lifetime processes in the plasma torus and of the excitation processes for the Lyman-α emission line. A significant amount of work has been expended to accomplish this objective as summarized briefly below.

The primary lifetime processes for atomic hydrogen are electron impact and charge exchange with H^+ and O^+:

$$H + e \longrightarrow H^+ + 2e \qquad \text{(R1)}$$
$$H + O^+ \longrightarrow H^+ + O \qquad \text{(R2)}$$
$$H + H^+ \longrightarrow H^+ + H \quad . \qquad \text{(R3)}$$

For plasma torus properties typical of the Voyager 1 spacecraft encounter time, approximate H lifetimes for these three reactions at Io's orbital position near western elongation are ~140 hrs, ~28 hrs, and ~13 hrs, respectively. The first lifetime value is based upon the assumption of an electron density of 2000 cm^{-3} and an electron temperature of 5 eV. The second lifetime is based upon a corotational speed of ~57 km sec^{-1} and an O^+ density of 1000 cm^{-3}. The third lifetime is based upon a corotational speed of ~57 km sec^{-1}, an ion temperature of 40 eV, and a likely H^+ density of 100 cm^{-3}. The large cross section for (R3) is the reason that this lifetime is about a factor of ~2 times smaller than the lifetime for (R2) even though the assumed density for H^+ is an order of magnitude smaller than the assumed density for O^+. The thermalized H^+ density in the plasma torus is not well known. The H^+ ion is so light that its pickup speed of ~57 km sec^{-1} is equivalent to only about 17 eV of gyrational kinetic energy, which is less than its assumed thermalized energy of ~40 eV with an equivalent Maxwell-Boltzmann average speed of ~88 km

sec^{-1}. Hence, an H^+ ion upon thermalizing with the heavy ions (O^+, O^{++}, S^+, S^{++}, etc.) of the plasma torus will actually increase its gyrational kinetic energy, in contrast to the heavy ions which decrease their gyrational kinetic energies. The reaction rate for (R3) thus depends both upon the corotational velocity and the ion temperature as illustrated in Figure 1. The implementation of the lifetimes for the three reactions above in the neutral cloud model is presently nearing completion.

Two excitation mechanisms for H Lyman-α emission (1216 Å) are being incorporated in the neutral cloud model. The first is electron impact

$$H(1s) + e \longrightarrow H(2p) + 2e \qquad \text{(R4)}$$

and the second is solar resonance scattering by H atoms. It has only been in the past decade that the electron impact Lyman-α excitation rate for atomic hydrogen has been effectively solved. This underscores the extreme difficulty of dealing accurately with the ultraviolet emission line rates of much heavier atoms, such as atomic oxygen and sulfur as discussed in section 2.1. The possible importance of excitation of H Lyman-α emission by ion impact with Io's atmosphere is also currently being assessed.

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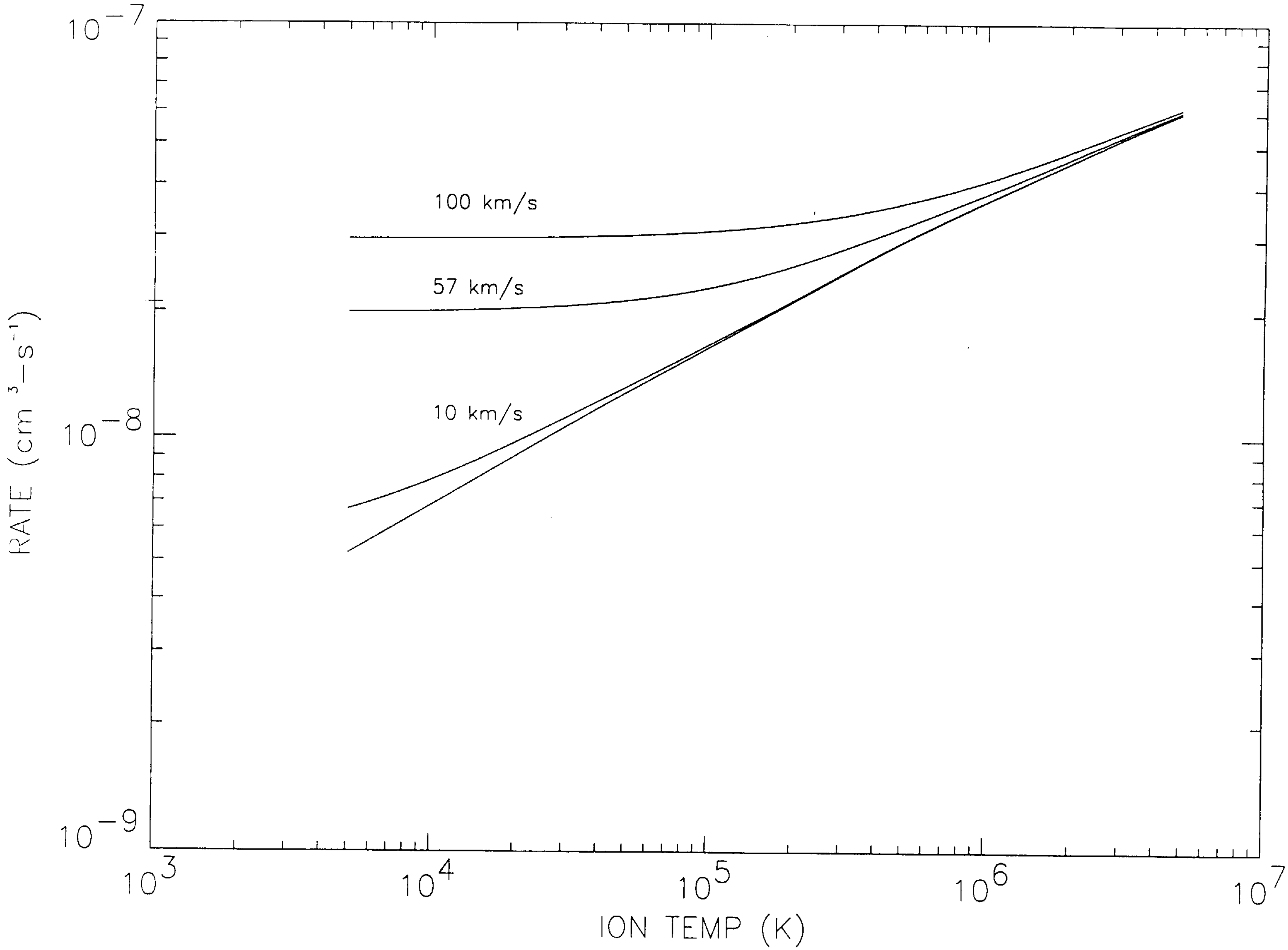
Table 1

Three Year Plan of Research for Studies for the Loss of Atomic and Molecular Species from Io

Subject	Year 1	Year 2	Year 3
Studies for the SO_2 Family	Analyze HST (cycle IV) UV data for O and S and available [O I] 6300 Å synoptic data for O using the O, S, SO and SO_2 cloud models; improve model execution time, update chemistry and refine the model description of the plasma torus.	Analyze the HST (cycle V) UV data for O and S; initiate analysis of Fabry-Perot image data for [O I] 6300 Å and [O I] 5577 Å (if relevant); re-analyze Voyager SO_2^+ data; determine sources rates and constraints on O, S, SO and SO_2 for the individual studies.	Complete analysis of UV and optical data; undertake the comparative and collective assessment of the individual studies for O, S, Na and SO_2^+ to probe the nature of the atomic and molecular species in Io's atmosphere and their implications for the Jupiter system.
Studies for Sodium	Continue the analysis of the 1987 east-west emission data set; initiate analysis of the same-date 1987 north-south emission data; refine model description of the plasma torus; re-evaluate the Na source at Io for the directional feature.	Complete analysis of the 1987 east-west emission data set; undertake analysis of other select years of the north-south emission data set; determine the nature and variability of the Na source conditions and their dependence on east-west and System III effects; analyze Fabry-Perot images for sodium and compare with [O I] 6300 Å images; assess the importance of the electron impact excitation and/or nonuniform gas distributions as a cause for asymmetric brightness distributions about Io.	

FIGURE CAPTION

Figure 1. Charge Exchange for Atomic Hydrogen and Plasma Torus Protons . The reaction rate for the process H + H^+ ----> H^+ + H as a function of the ion temperature and corotational speed (0, 10, 57, 100 km sec^{-1}) is shown. The cross sections for this process were obtained from Schutz et al. (1995) and Janev and Smith (1993).



10^{-7}
10^{-8}
10^{-9}
RATE (cm^3-s^{-1})
100 km/s
57 km/s
10 km/s
10^3
10^4
10^5
10^6
10^7
ION TEMP (K)

Figure 1

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Continued effort is reported to improve the emission rates of various emission lines for atomic oxygen and sulfur. Atomic hydrogen has been included as a new species in the neutral cloud model. The pertinent lifetime processes for hydrogen in the plasma torus and the relevant excitation processes for H Lyman-α emission in Io's atmosphere are discussed.

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